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Lateral Interception I: Operative Optical Variables, Attunement, and Calibration

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J. J. Gibson (1966, 1979) suggested that improvement in perception and action can be attributed in part to changes in which variable is attended to. Such reattunement has been demonstrated with observers making judgments in response to simulations. The present study sought attunement changes in the perception of real events and in visually guided action. In 3 experiments, adults judged the passing distance of or attempted to catch balls. Discrete measures and the predictions of a modified required velocity model (e.g., R. J. Bootsma, V. Fayt, F. T. J. M. Zaal, & M. Laurent, 1997) were used to reveal which variables were exploited. Participants differed from each other and, to some extent, changed in the optical variables used, in catching as well as judging. Nevertheless, the changes were much smaller than in previous simulation-judgment studies; calibration was also found to underlie the improvements in performance.

Keywords: perception–action, interception, learning, calibration

Perception and visually guided action often improve with practice. A well-documented example of such an improvement is found in sexing day-old chicks (Biederman & Shiffrar, 1987; E. J. Gibson, 1969; Lunn, 1948). After extended periods of training, professional sexers can classify male and female chicks with great accuracy, looking only briefly at the genital eminences of the birds, whereas novices perform barely above chance level. An equally striking example is the high speed and accuracy demonstrated by Japanese technicians who detect and classify defective food cans by tapping them with a steel probe (Okura, 1999). Why are experts so much better than novices? What are the changes underlying the improvement?

J. J. Gibson (1966, 1979; see also E. J. Gibson, 1969; E. J. Gibson & Pick, 2000; Michaels & Carello, 1981) suggested that, with experience, perceivers and actors become attuned to the more useful information variables, a process he referred to as the *education of attention*. Such a learning process has been demonstrated, for instance, in the visual perception of pulling force (Michaels & de Vries, 1998; cf. Jacobs, Michaels, Zaal, & Runeson, 2001), the distance and size of freely falling balls (Jacobs & Michaels, 2001), and the relative mass of colliding balls (Jacobs, Michaels, & Runeson, 2000; Jacobs, Runeson, & Michaels, 2001; Runeson, Juslin, & Olsson, 2000). In all these studies, observers differed from one another and changed in the optical variables they used. Before practice, judgments were often based on optical variables that correlated marginally with the property to be judged. After practice with feedback, observers flexibly converged on the more useful optical variables.

The apparent differences and changes in variable use are important because they run counter to the assumption that individuals always rely on the same optical variable under the same circumstances. This assumption underlies many theoretical and empirical studies in the fields of perception and visually guided action. Many experimenters seem to take as their aim either revealing that a particular optical variable (e.g., tau) constrains perception or action in some task or, conversely, showing that a variable does not so constrain perception or action (e.g., Lee & Reddish, 1981; Lee, Young, Reddish, Lough, & Clayton, 1983; Savelsbergh, Whiting, & Bootsma, 1991; van der Kamp, 1999). The relevance of demonstrations of use or nonuse of a particular variable depends on the range of situations to which the demonstration applies. The abovementioned differences and changes in variable use indicate that, at least in some cases, this range can be narrow.

Two issues, however, might limit the generalizability of the experiments that revealed individual differences and changes in variable use (i.e., Jacobs et al., 2000; Jacobs & Michaels, 2001; Jacobs, Michaels, et al., 2001; Jacobs, Runeson, & Michaels, 2001; Michaels & de Vries, 1998; Runeson et al., 2000). First, stimuli were always presented as two-dimensional displays, and, second, observers always made judgments. Are the cited differences and changes mere peculiarities of making judgments in response to two-dimensional simulations, or are they general characteristics of

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perception and visually guided action? Some anecdotal support for the generality of these findings has been provided by Pickering (1998), who argued that attunement to adequate visual and auditory variables is an essential aspect of learning to cycle through crowded city streets in India. In the present study we attempt a more formal test.

Participants in the present study observed balls that swung down on thin lines, passing at small sideward distances—a task first examined in detail by Peper, Bootsma, Mestre, and Bakker (1994; see Figure 1). We asked participants in Experiment 1 to judge passing distance and participants in Experiments 2 and 3 to actually catch the balls. Although judging and catching are not necessarily novel tasks (baseball batters discriminate strikes from balls, and lateral catching is common), it was our hope that balls swinging down on strings and at various angles would provide a sufficiently novel challenge to permit improvements in performance with practice. Failing that, monocular viewing might also challenge judgers and catchers to attend to new variables. We used this task also because the optical variables and control laws that might govern one-handed catching have been examined extensively (e.g., Bootsma, 1988; Bootsma, Fayt, Zaal, & Laurent, 1997; Bootsma & Oudejans, 1993; Bootsma & Peper, 1992; Montagne, Fraisse, Ripoll, & Laurent, 2000; Montagne, Laurent, Durey, & Bootsma, 1999; Peper et al., 1994; Rosengren, Pick, & von Hofsten, 1988).

Peper et al. (1994) sought to determine whether perceivers and actors were able to detect information that specified future passing distance. At the outset of their investigation, Peper et al. hypothesized a *predictive strategy*; that is, they hypothesized that catchers could predict the place and time of the future interception and use

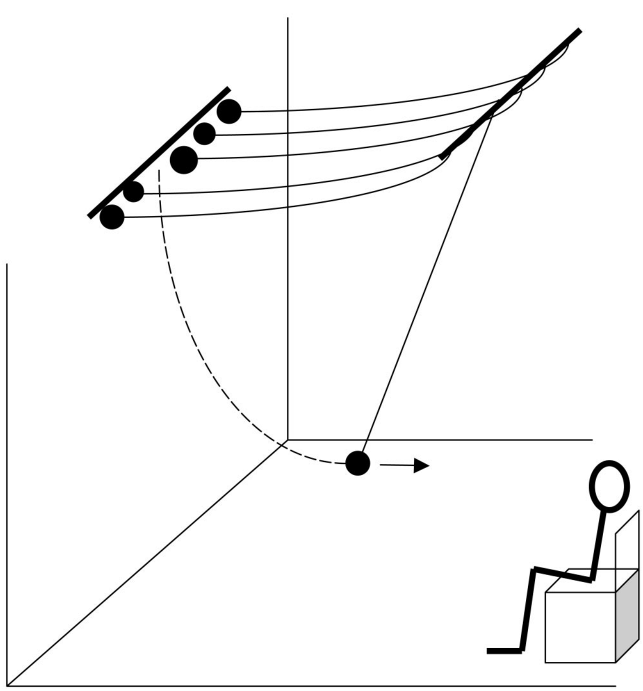

Figure 1. Experimental set-up. Balls swung down on thin lines and passed at some distance to the right of the perceiver/actor. Note that the lines in the figure are parallel only for illustration purposes; in the experiments they were crossed.

these predictions to control their hand movement. However, the kinematics of actual catches and systematic errors in verbal judgments of passing distance led Peper et al. to reject predictive strategies in favor of *continuous control strategies* (see also Bootsma & van Wieringen, 1988, 1990; Dessing, Bullock, Peper, & Beek, 2002; McLeod & Dienes, 1993, 1996; Michaels & Oudejans, 1992; and Oudejans, Michaels, Bakker, & Davids, 1999, for the distinction between predictive and continuous strategies). Peper et al. concluded that catchers establish and maintain a certain information–movement relation that leads the hand to the right place at the right time, regardless of where and when this is.

Peper et al. (1994) presented a continuous control model that explains a range of empirical findings. This *required velocity model* has been elaborated by Bootsma et al. (1997) and empirically supported by Montagne et al. (1999, 2000). We present a slightly modified version of the model in the introduction of Experiment 2. For now it suffices to note that we assume continuous control and investigate which variables participants couple their movements to, which variables they base their judgments of passing distance on, and whether they change in which variables they use. We next describe in some detail the candidate optical variables.

Figure 2 schematically presents an approaching ball that crosses the eye plane of the observer at a small sideward distance. Physical parameters of interest are the approach angle, A; the diameter of the ball, D; the momentary lateral distance of the ball, X; and the passing distance of the ball, X_c. Optical variables relevant to the present study are the angular size of the ball, ϕ; the horizontal spherical (azimuthal) angle to the center of the ball, θ; the temporal derivatives of these angles, $\dot{\phi}$ and $\dot{\theta}$; the ratio of the angles, θ/ϕ; and the ratio of the derivatives, $\dot{\theta}/\dot{\phi}$.

The ratio $\dot{\theta}/\dot{\phi}$ resembles the ratio of the image-plane variables of lateral optical velocity and optical expansion (not shown in Figure 2) discussed by Bootsma and Peper (1992). Bootsma and Peper showed that this ratio does not change during the approach and that it specifies future passing distance in units of ball size, under the assumptions that the object approaches on a straight trajectory with a constant velocity and that the object is flat (so that foreshortening occurs). Because these assumptions did not hold in our experiments, the ratios did change during the approaches. Nevertheless, at particular moments of the approaches, $\dot{\theta}/\dot{\phi}$ and the ratio of lateral image velocity to image expansion correlated highly with each other and with future passing distance in units of ball size.

In situations in which balls of different sizes are used, however, passing distance in units of ball size and also the variable $\dot{\theta}/\dot{\phi}$ are of limited usefulness. Imagine a ball that passes at a particular distance and another ball, half as large, that passes at the same distance. Obviously, in units of ball size, the passing distance is twice as big for the smaller ball, but the catcher needs to catch the balls at the same location. In the present experiments, we used balls of different sizes. Can one identify optical patterns that are related to future passing distance even in such a more general situation?

Let us start from the assumption that optical information about ball size exists, information we refer to as δ. Given that the optical pattern $\dot{\theta}/\dot{\phi}$ is closely related to passing distance if balls of the same size are used, the optical pattern $\delta \times \dot{\theta}/\dot{\phi}$ is closely related to future passing distance even if ball size varies, which makes it

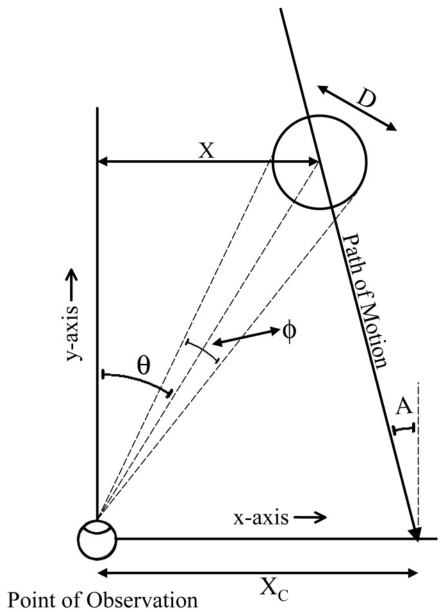

Figure 2. The geometry of an approaching ball. Capital letters denote physical variables, and Greek symbols denote optical variables. A = approach angle; D = diameter of ball; X = lateral distance of ball; X_C = passing distance; ϕ = angle subtended by ball; θ = azimuthal angle, which is equal to the angle between the sagittal plane and a line from the eye to the center of the ball.

a variable of interest for lateral interception.[1] It is worth noting that there are both monocular and binocular variables that specify ball size in this task. For the binocular case, convergence angle or disparity could be involved; for the monocular case, vertical angle could be involved. For instance, given the (local) constraint of pendular motion and the consistency of the vertical trajectories, vertical angle essentially specifies current ball distance, and, thus, vertical angle together with the optical size of the ball specifies ball size.[2]

In summary, in the present study we evaluate candidate optical variables to find which best predict judgments of passing distance and of lateral interceptive actions. We are particularly interested in the extent to which perceivers differ and change in the variables on which they base judgments of a natural event, as opposed to a two-dimensional display, and in the extent to which actors differ and change in the variables to which they couple their movements, as opposed to only their judgments. Participants in Experiment 1 made verbal estimates of passing distance. Participants in Experiment 2 reached to catch balls while their hands were restricted to move in a single dimension. In Experiment 3, participants reached to catch balls without such a restriction on the hand movements.

Experiment 1

The main purpose of Experiment 1 was to replicate the finding that observers differ and change in the variables they use in making verbal judgments. In contrast to earlier studies, we used real events rather than two-dimensional simulations and an experimental setting in which actions could be solicited in subsequent experiments. Participants observed approaching balls until a short time interval before the balls would pass; they were asked to estimate the distance (from their right eye) at which the balls crossed their eye plane. To reveal the hypothesized changes in variable use, we included in the experiment a pretest, a practice phase with feedback, and a posttest. We analyzed which optical variables explained most of the variance in the judgments. The candidate variables were $\dot{\theta}/\dot{\phi}$, $\delta \times \dot{\theta}/\dot{\phi}$, and $\theta/\dot{\phi}$. Remember that $\dot{\theta}/\dot{\phi}$ and $\delta \times \dot{\theta}/\dot{\phi}$ are related to future passing distance, either under the constraint of single-sized balls or with variable ball size, respectively.[3]

The values of the candidate variables changed continuously during the approaches. We assumed that observers rely on the values just before vision is occluded and computed the Pearson product–moment correlations between passing distance and the values of the candidate variables at that moment and among the values of the candidate variables at that moment (see Table 1). The squared correlation between $\delta \times \dot{\theta}/\dot{\phi}$ and actual passing distance was .99, which means that the use of this variable and appropriate calibration could yield highly accurate judgments. The squared correlations between passing distance and $\dot{\theta}/\dot{\phi}$ and $\theta/\dot{\phi}$ were .76 and .26, respectively, indicating that the use of these variables would yield less accurate performance.

Method

Participants. Six male and 2 female students were paid for their participation. Their mean age was 23 years (range = 18–26). All reported normal or corrected-to-normal vision, and their stereoacuity was at least 60 s arc^{-1} (Polaroid 3-D Vectograph, Titmus Optical Inc., Petersburg, VA).

Apparatus. Ten black rubber balls with diameters of 4.38, 4.71, 5.67, 6.37, and 7.38 cm were suspended from a ceiling rail 6.12 m above the floor with 5.22-m long, thin, monofilament fishing line (see Figure 1). The leftmost line was attached to the ceiling rail 41.5 cm to the right of the observer's sagittal plane; the other lines were attached farther to the right, separated by 3-cm intervals. Before each series of 10 trials, the balls were attached to computer-controlled solenoids on a second rail 4.99 m above the floor. The leftmost solenoid was placed 1.3 cm to the left of the observer's sagittal plane; the other solenoids were placed to its right, separated by 12.5-cm intervals. The balls remained suspended from the same suspension point on the ceiling rail throughout the experiment. However, within each series of 10 trials, the balls were randomly assigned

[1] Note that, from an ecological point of view, $\dot{\theta}/\dot{\phi}$ and $\delta \times \dot{\theta}/\dot{\phi}$ have the same ontological status as, for instance, variables such as δ. That is, although $\dot{\theta}/\dot{\phi}$ and $\delta \times \dot{\theta}/\dot{\phi}$ might appear complicated, such apparent complexity is no reason to assume that they are complicated for perceptual systems to detect. Let us briefly illustrate this. We could rename, for instance, variable $\delta \times \dot{\theta}/\dot{\phi}$ as variable X and variable $\dot{\theta}/\dot{\phi}$ as variable Y and describe δ as X/Y. For someone familiar with this nomenclature, X/Y (i.e., δ) might appear more complicated than X or Y (i.e., $\delta \times \dot{\theta}/\dot{\phi}$ or $\dot{\theta}/\dot{\phi}$). Apparent complexity, then, depends on largely arbitrary descriptive systems and thus does not determine the ontological status of variables.

[2] Given that the present study indicates that $\dot{\theta}/\dot{\phi}$ and, more so, $\delta \times \dot{\theta}/\dot{\phi}$ are frequently used by catchers, our companion article (Michaels et al., 2006) uses them in the modeling of catches. The companion article also considers possible embodiments of δ in more detail.

[3] More extended but not presented analyses considered additional variables, including the angle of elevation of the ball and information specifying the momentary lateral distance of the ball, later referred to as χ_{ball}. These variables were not significant predictors of judgments.

to the release solenoids. The order in which they were released was also chosen randomly within each series of 10 trials. The resulting trajectories intersected the eye plane at distances of 18 to 92 cm and at incidence angles of −7.8° to 7.8°. Participants were seated so that the balls crossed the eye plane at eye level and at 1.80 m (as projected on a horizontal surface) after reaching the lowest point in the trajectory. The time between the moment that a ball was released and the moment it crossed the eye plane was 1.57 s. Liquid crystal goggles were used to allow and restrict vision.

Design and procedure. The experiment consisted of a 60-trial pretest, four 60-trial practice blocks, and a 60-trial posttest. Participants verbally reported the distance at which the ball crossed their eye plane. The reports were in centimeters from the participant's right eye. In the practice blocks, the experimenter reported the actual distance immediately after the observer gave his or her judgment. After each series of 10 trials there was a 2-min break, during which the experimenters reattached the balls to the solenoids. After each set of 60 trials there was a 10-min break. The experiment was run in two 2-hr sessions, typically conducted on consecutive days. The first session included the pretest and the first two practice blocks, and the second session included the final two practice blocks and the posttest.

Four participants observed monocularly, and 4 observed binocularly. The goggles—only the right glass in the monocular condition—opened between 0.6 and 0.8 s after ball release and closed between 1.3 and 1.4 s after ball release.[4] Within these intervals, the opening and closing times were chosen randomly. Observers were asked not to change their posture. Although small differences and changes in the position of the eye were inevitable, they were negligible compared with the large movements of the ball. This is important because in the computation of the values of the optical variables from known position of the balls, we assumed that the eye position was constant.

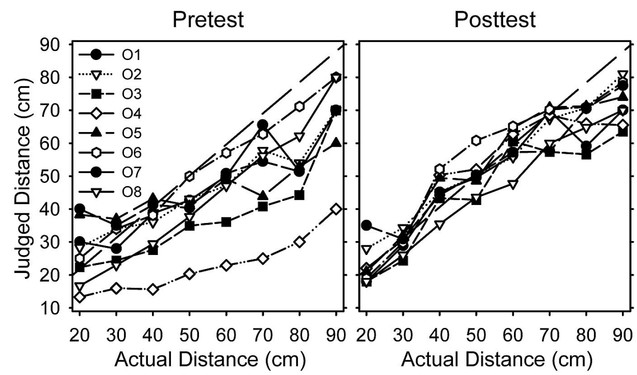

Figure 3. Average judged passing distances for individual observers, given as a function of actual passing distances in the pretest (left) and posttest (right) of Experiment 1. Observers (Os) 1 to 4 viewed the balls monocularly, and Observers 5 to 8 viewed them binocularly.

Results and Discussion

We first analyzed whether observers were able to judge passing distance and whether they improved with practice. Figure 3 shows the average judged passing distance for each participant as a function of the actual passing distance (blocked into 10-cm intervals) in the pretest (left panel) and in the posttest (right panel). Most averages reasonably approximated the actual distances, which indicates that observers were able to perceive passing distance, at least to some extent. Figure 3 also seems to indicate that the judgments approximated the actual distances more closely in the posttest than in the pretest.

To test whether these improvements were reliable, we performed an analysis of variance (ANOVA) on the absolute errors—that is, on the average of the absolute differences between the judgments and the actual passing distances. Block (pretest, posttest) was a within-subjects factor, and vision (monocular, binocular) was a between-subjects factor. Only the effect of block was significant, $F(1, 6) = 8.2$, $p < .05$, indicating that observers performed better after practice than before.[5] The average absolute error was 16.5 cm in the pretest and 9.3 cm in the posttest. In sum, observers seemed able to perceive passing distance, and their judgments improved after practice with feedback.

To determine which optical variables explained most of the variance in the judgments, we computed the Pearson product–moment correlations between the judged distances and the value of the three candidate optical variables at the moment of goggle closing. We reasoned that the use of a particular candidate variable would be consistent with a higher correlation between that variable and the judgments than between other candidate variables and the judgments (cf. Michaels & de Vries, 1998). Figure 4 presents squared correlations for each block of trials for each observer. The judgments of Observers 1 to 4, who viewed the balls monocularly, seemed to be best explained by $\dot{\theta}/\dot{\phi}$ (dots) in the pretest. The judgments of Observers 1 and 3 continued to correlate most highly with this variable throughout the experiment, whereas the judgments of Observer 4 correlated most highly with $\dot{\theta}/\dot{\phi}$ or θ/ϕ (squares) in the latter blocks. Recall that $\dot{\theta}/\dot{\phi}$ and θ/ϕ correlated less than perfectly with passing distance ($r^2 = .76$ and .26, respectively), which means that their use implied a lower performance level. Despite the corresponding feedback, the correlations of the judgments of Observers 1, 3, and 4 did not suggest a change to reliance on a more useful variable. The judgments of Observer 2, conversely, correlated most highly with $\delta \times \dot{\theta}/\dot{\phi}$ (open triangles)

Table 1
Squared Correlations Among Actual Passing Distance and the Candidate Optical Variables in Experiment 1

Variable	1	2	3	4
1. Passing distance	—	.76	.99	.26
2. $\dot{\theta}/\dot{\phi}$		—	.76	.61
3. $\delta \times \dot{\theta}/\dot{\phi}$			—	.26
4. θ/ϕ				—

Note. We used the values at the moment that the goggles closed. The goggles closed earlier for Observers 5 and 6, which led to slightly different squared correlations. See footnote 4 for details.

[4] Because of a programming error, the goggles opened and closed 0.3 s earlier for Observers 5 and 6. This affected the correlations presented in Table 1. Most relevant, for these 2 observers, the squared correlations between passing distance and $\dot{\theta}/\dot{\phi}$, $\delta \times \dot{\theta}/\dot{\phi}$, and θ/ϕ were .74, 1.00, and .22, respectively. We did not replace the observers because their results did not appear to deviate from the results of the other observers.

[5] In all significance tests on performance measures with the factors block and vision condition, we used single-tailed tests. In all cases, we expected performance to be better in the binocular condition and to improve with practice.

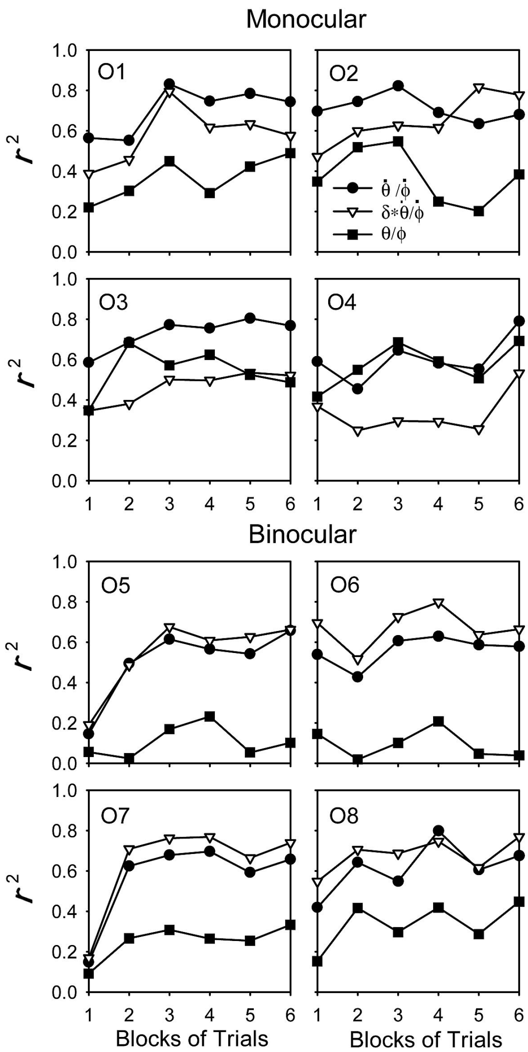

Figure 4. The squares of the correlations between the candidate optical variables and the judgments of passing distance in Experiment 1. Each plot shows the results for one observer (O).

in the final two blocks.[6] This variable correlated highly with the to-be-perceived distance ($r^2 = .99$) and could thus lead to accurate judgments and satisfactory feedback. There appeared to be fewer differences and changes in the binocular condition; in most blocks of trials, the judgments of Observers 5 to 8 correlated most highly with $\delta \times \dot{\theta}/\dot{\phi}$.[7]

Altogether, Figure 4 suggests that monocular observers tended to rely on $\dot{\theta}/\dot{\phi}$ and binocular observers on $\delta \times \dot{\theta}/\dot{\phi}$ and that practice with feedback did not have a strong effect on which optical variables were used. To test whether these effects were reliable, we computed a dependent measure that represents the relative value of $\dot{\theta}/\dot{\phi}$ and $\delta \times \dot{\theta}/\dot{\phi}$ in explaining the judgments: the difference between the Fisher *z* transformations of the correlations between the judgments and $\dot{\theta}/\dot{\phi}$ and $\delta \times \dot{\theta}/\dot{\phi}$. We performed an ANOVA on this dependent measure, with block (pretest, posttest) as a within-subjects factor and vision (monocular, binocular) as a between-subjects factor. Only the effect of vision was significant, $F(1, 6) = 22.9$, $p < .01$. Indeed, the judgments of monocular observers correlated more highly with $\dot{\theta}/\dot{\phi}$, and the judgments of binocular observers correlated more highly with$\delta \times \dot{\theta}/\dot{\phi}$.

Although Observer 2 changed and came to rely on a more useful variable, it seems improbable that the small changes in variable use can explain the large improvement of performance as measured, for instance, by the decrease in absolute error. How, then, should we understand this decrease in error? We suggest it might depend on calibration. The ecological approach, to which we subscribe, proposes that perception is a single-valued function of an information variable (e.g., an optical pattern; Michaels & Beek, 1995; Michaels & Carello, 1981; Turvey, 1996). In this view, one can understand calibration as the process by which the single-valued function becomes adjusted to the requirements that the environment imposes on the perceiver (see Bingham & Pagano, 1998, for a discussion of calibration and the general need for calibration). To anticipate the following analyses and, more important, the analyses of actual catches in Experiment 2, we now describe some implications of this view of calibration.

If judgments are indeed a single-valued function of optical patterns, one needs to know or assume what single-valued function is involved to test whether judgments are related to a particular optical variable. Our use of correlation analyses to measure the dependence of judgments on optical variables indicates that we assumed (and later confirmed in the scatter plots) that the single-valued function was a linear one, which is to say that, at each phase of the experiment,

$$J = c_1 O + c_2, \tag{1}$$

in which J is a judgment, O is the operative optical variable, and c_1 and c_2 are parameters. Because calibration is interpreted as change in the single-valued function that relates a judgment to the operative optical variable, calibration can be operationalized as change in the parameters c_1 and c_2, which we therefore refer to as *calibration parameters*. We now address possible changes in these calibration parameters over blocks of trials.

Figure 5 presents the values of parameters c_1 and c_2 (upper and lower panels, respectively) for monocular and binocular observers

[6] A reviewer-suggested interpretation of the apparent shift from $\dot{\theta}/\dot{\phi}$ to $\delta \times \dot{\theta}/\dot{\phi}$ is that on later blocks participants perceived ball size at the beginning of an approach and used that to calibrate $\dot{\theta}/\dot{\phi}$. First, note that this is a different usage of *calibration* from ours; we use *calibration* to refer to effects that occur over trials, independent of the informational flow on a particular trial. However, although we subscribe to a direct perception account and refer to a shift from reliance on $\dot{\theta}/\dot{\phi}$ to reliance on $\delta \times \dot{\theta}/\dot{\phi}$, others might prefer to think of a piecemeal pickup of variables where δ is added. In either case, the performance change reflects a change in attunement; information that was not used on a prior trial begins to be used.

[7] Although one could perform statistical tests on all pairwise comparisons of correlations within each block of trials of each observer (Michaels & de Vries, 1998), we present more global tests showing that the main findings were significant. In addition, we report in this footnote a change in pattern of correlations that is crucial for the hypothesis. For Observer 2, the difference between the correlations of judgments with $\dot{\theta}/\dot{\phi}$ and with $\delta \times \dot{\theta}/\dot{\phi}$ was significant ($p < .01$) in Blocks 1, 2, 3, and 5. This means that the change in which variable explained most of the variance in the judgments of this observer was significant.

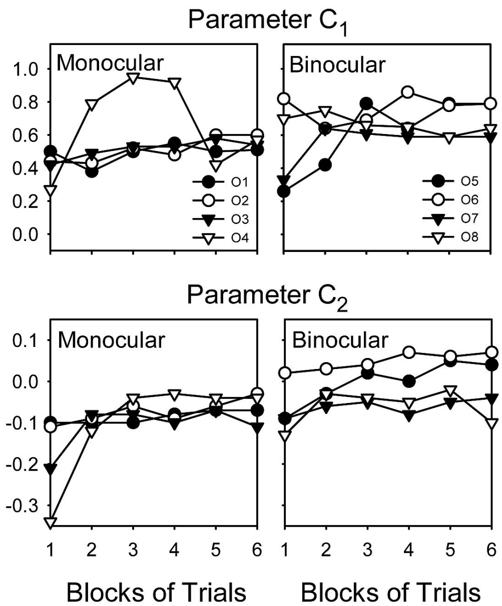

Figure 5. Calibration parameters determined for Experiment 1. The top panels show c_1, the slope of the regression lines relating judgment to the best fitting optical variable. The bottom panels show c_2, the intercept of the line, as described in footnote 8. O = observer.

(left and right panels, respectively), as determined from linear regressions of judgments against values at goggle closing of the optical variable that the particular participant appeared to exploit on that block of trials.[8] On average, c_1 was .47 in the pretest and .63 in the posttest, and c_2 was −.13 in the pretest and −.04 in the posttest. We performed separate ANOVAs on these parameters; block (pretest, posttest) was a within-subjects factor, and vision (monocular, binocular) was a between-subjects factor. The effect of block was significant for parameter c_2, $F(1, 6) = 9.2$, $p < .05$, and marginally significant for parameter c_1, $F(1, 6) = 4.6$, $p < .10$. None of the other effects was significant (i.e., $p > .10$). In sum, the most notable result of these analyses is that calibration parameter c_2 was closer to zero in the posttest than in the pretest, indicating that the judgments were better calibrated after practice.

We conclude that the improvement in the distance judgments should be attributed both to calibration and to attunement. We observed less change in variable use than in previous experiments, in which the stimuli were presented on two-dimensional displays and the tasks (e.g., judging force or relative mass) were arguably less familiar than judging distance. Nevertheless, some observers in the current experiment changed in the variables they used, and there were large differences between the variables used by monocular and binocular observers. Monocular observers seemed to rely mostly on $\dot{\theta}/\phi$ and binocular observers on $\delta \times \dot{\theta}/\dot{\phi}$.

Experiment 2

Experiment 1 showed that practice with feedback affected the calibration of verbal judgments of passing distance and, to a lesser extent, the attunement to optical variables. Do these effects obtain in visually guided action? We asked participants in Experiment 2 to actually catch the balls. Apart from the response—catching balls instead of judging passing distance—we made Experiment 2 as similar as possible to Experiment 1; we used the same apparatus, balls, vision conditions, pretest–training–posttest design, and so forth. The main purpose of the analyses was also similar—namely, to discover the operative optical variables and the extent to which there are differences and changes in variable use and calibration.

A major challenge in analyzing which optical variables are used for the guidance of a movement is that one does not generally know how the used variable constrains the movement. Only if one knows or assumes how the variable informs the movements can one test whether movement kinematics relate to a particular optical variable. We used the catching paradigm in part because previous studies identified (Bootsma et al., 1997; Peper et al., 1994) and empirically supported (Montagne et al., 1999, 2000) a control law that might govern catching, the required velocity model (see Warren, 1988, for an ecological view on the concept of control law). Our strategy to determine the exploited variable was to use the candidate variables as the input of this model and see which of them led to the best movement predictions.

Let us now examine the required velocity model in more detail. The model holds that the acceleration of the hand of a catcher, A_{hand}, is a function of the momentary velocity of the hand, V_{hand}, and the required velocity of the hand, $V_{\text{hand-required}}$. The required velocity of the hand, in turn, is a function of the momentary lateral position of the hand, X_{hand}, the momentary lateral position of the ball, X_{ball}, and the first-order time remaining before the ball reaches the interception point, TC_1 (see Bootsma et al., 1997, for details on the concept of first-order time remaining). More precisely, the control law states that

$$A_{\text{hand}} = \alpha V_{\text{hand-required}} - \beta V_{\text{hand}}, \tag{2}$$

where α and β are model parameters, and that

$$V_{\text{hand-required}} = (X_{\text{ball}} - X_{\text{hand}})/TC_1. \tag{3}$$

The model assumes that the position and speed of the hand are specified and that catchers are sensitive to this information, which is presumably kinesthetic and may be partly optical when the hand is in sight. The model also assumes that the momentary lateral position of the ball is specified by optical patterns and that observers use such information. Peper et al. (1994) and Bootsma et al. (1997) did not investigate which optical patterns might be involved.

We modified the model on three points. First and foremost, we did not assume that observers relied on information that specifies

[8] One should note that, in contrast to the previously presented correlation analyses, the values of the calibration parameters depend on the units and zero points that one chooses to use for the optical variables and judgments. We defined the optical variables in meters. To achieve that, we multiplied the dimensionless $\dot{\theta}/\phi$ and θ/ϕ by average ball size. The units of $\delta \times \dot{\theta}/\dot{\phi}$ depend on the units of δ, which we assumed to be in meters. These (largely arbitrary) definitions are convenient because the so-defined variables have approximately equal means. We used this mean as the zero point of the optical variables. Furthermore, we used average passing distance as the zero point for the judgments, which implied transforming the judgments (i.e., subtracting average passing distance, which was 0.55 m). Because of this transformation, the optimal value of c_2, the intercept, was about zero.

the momentary lateral distance of the ball, which we refer to as χ_{ball}. Instead, we consider χ_{ball} to be a candidate variable along with those variables that monocular and binocular observers appeared to use in Experiment 1, $\dot{\theta}/\dot{\phi}$ and $\delta \times \dot{\theta}/\dot{\phi}$. Remember that the latter two variables are related to future passing distance, the former under the constraint of single-sized balls and the latter not. Thus, one can intuitively understand our analyses as investigating whether catchers use optical variables that continuously guide the hand toward (a) the momentary lateral position of the ball, (b) the future passing distance in units of ball size, or (c) the future passing distance.

Second, we exchanged the parameters α and β for the parameters c_1 and c_2. Although Bootsma et al. (1997) showed that one can use different values of α and β to model the different kinematics of catching and hitting, the parameters have no clear interpretation, and, in our judgment, they reduce the logic of the model. It seems reasonable to assume that the hand accelerates to decrease the difference between the actual and the required velocity. This is not always predicted if α and β are allowed to be different. Consider, for instance, a situation in which the required and actual velocities are equal. Here, a difference between α and β would predict that the hand accelerates away from the required velocity. In the modified model, α and β are replaced by a single parameter, c_1. We show below that, analogous to the analyses of judgments reported in Experiment 1, c_1 can be interpreted as a calibration parameter and also that it is desirable to introduce c_2 as a second calibration parameter.

Third, we changed the physical variable TC_1 for the optical variable $(\dot{\phi}/\phi - \dot{\rho}/\rho)^{-1}$, where ρ is $\pi/2 - \theta$. Bootsma and Peper (1992) showed that this optical variable specifies time to contact for objects that do not approach head on. The specificity depends on a few assumptions, including a constant velocity, a linear trajectory, and small angles ϕ and ρ. Despite considerable violations of these assumptions, $(\dot{\phi}/\phi - \dot{\rho}/\rho)^{-1}$ reasonably approximated first-order time to contact in our experiments; at the moment of goggle closure, for instance, the squared correlation between these two variables was .94 ($p < .001$).

The resulting control law can be described by the differential equation

$$A_{\mathrm{hand}} = c_1\left(\frac{c_2 O - X_{\mathrm{hand}}}{(\dot{\phi}/\phi - \dot{\rho}/\rho)^{-1}} - V_{\mathrm{hand}}\right) \tag{4}$$

in which O—the optical variable—can be either $\dot{\theta}/\dot{\phi}$, $\delta \times \dot{\theta}/\dot{\phi}$, or χ_{ball}. Because O need not be in the same units as the (presumably) kinesthetic information about hand position, a parameter might be required to integrate these otherwise incommensurable variables into a single value. This is parameter c_2, which represents how the optical variable is calibrated with respect to the kinesthetic variable.[9] Analogously, without c_1 the units of the left and the right side of Equation 4 would not match. If one interprets the right side of the equation without c_1 as a higher order variable that specifies a required acceleration, one can interpret c_1 as indicating how this variable is used; it indicates which value of the higher order variable leads to which acceleration.

In summary, the purpose of Experiment 2 was to discover (a) which of the candidate variables, in combination with Equation 4, best explains the kinematics of catching; (b) whether actors differ from each other and change in which variables they use; and (c) whether there are differences among actors and changes in the best fitting calibration parameters.

Method

Eight right-handed students were paid for their participation. Four were male, and 4 were female. Their mean age was 21 years (range = 18–26). All reported normal or corrected-to-normal vision, and their stereoacuity was at least 60 s arc^{-1}. None of them had ever participated in a similar experiment. We used the same apparatus as we had in Experiment 1, but here we asked observers to actually catch the balls. Their hands were attached to a horizontal bar allowing movement only in a single dimension. The bar was positioned 1.62 m behind the lowest point of the trajectory of the balls, 0.23 m in front of the eye plane. The time between release and the moment the ball crossed the rail was 1.54 s. We chose the starting position of the hand randomly from the interval between 35 and 67 cm to the right of the participant's right eye. To allow comfortable reaches at all passing distances, we did not use the more extreme combinations of the suspension points on the ceiling rail and the solenoids from which the balls were released. As a result, the balls passed at distances ranging from 27 to 75 cm from the right eye of the seated participant and at incidence angles of −6.8° to 6.8°.

We used the same balls, goggle opening and closing times, and monocular and binocular vision conditions that we used in Experiment 1. Also as in Experiment 1, we used a 60-trial pretest, four 60-trial practice blocks, and a 60-trial posttest. In the test phases, in which no feedback was to be given, a second bar was positioned in front of the bar along which the hand moved. This bar stopped the balls just before they would have been caught, touched, or missed and thereby ensured that observers did not have haptic feedback. In these blocks, participants were asked to move their hand and fingers as if they were actually catching the balls. Earplugs and the closing of the goggles ensured that observers did not have auditory or visual feedback. In the practice blocks, the earplugs were not used, and the ball paths were not obstructed so that participants could catch, touch, or miss the balls. Therefore, participants had haptic feedback on the practice trials. On all trials, the three-dimensional coordinates of a marker on the back of the hand were registered at 100 Hz with an Optotrak movement registration system. In addition, the experimenters scored whether the balls were caught, touched, or missed. The experiment was conducted in two 2-hr sessions.

Results and Discussion

This section addresses (a) the improvement with practice, (b) the optical basis of the hand movement analyzed with the assumed control law, (c) the optical basis analyzed with a discrete action parameter, and (d) the calibration of the movement.

Improvement with practice. Figure 6 shows the percentages of the balls that were caught, touched, and missed in the practice blocks for monocular observers (left panel) and binocular observers (right panel). Recall that the balls could not actually be caught in Blocks 1 and 6. On average, monocular participants caught 46% of the balls, and binocular participants caught 80%. We performed

[9] Although the model did not require this, we defined the candidate variables in meters (see Footnote 8). Because of this definition, the candidate variables might not be incommensurable with hand position without calibration parameter c_2, but we can still use c_2 to analyze how observers calibrate the optical and the kinesthetic variables. As we also described in Footnote 8, these definitions made the averages of the so-defined variables approximately equal, allowing us to consider the same range of calibration parameters for each variable.

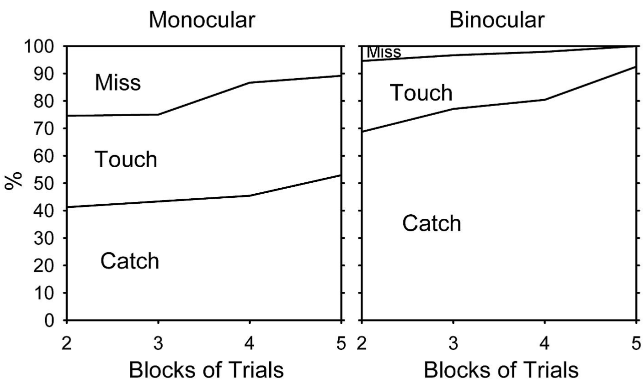

Figure 6. Percentages of balls that were caught, touched, and missed in the practice blocks of Experiment 2.

an ANOVA on the number of catches; block (2 to 5) was a within-subjects factor, and vision (monocular, binocular) was a between-subjects factor. Both factors were significant: $F(3, 18) = 9.0$, $p < .01$, for block, and $F(1, 6) = 10.3$, $p < .05$, for vision. This means that performance improved with practice and that more balls were caught in the binocular condition. The interaction was not significant, $F(3, 18) = 1.0$, $p = .41$.

Optical basis of the movement as analyzed with the assumed control law. To determine which optical variables participants appeared to use, we computed the hand movements predicted by each candidate variable and then compared the predicted and actual kinematics. We illustrate how we predicted the kinematics using a single trial as an example. Consider Figure 7. The horizontal axis represents time to contact (t). The ball is released at $t = 1.54$ and reaches the interception point at $t = 0.00$. The dashed verticals at $t = 0.84$ and $t = 0.15$ indicate the opening and closing of the goggles on that trial. The vertical axis gives the distance to the right of the observer's right eye (i.e., X in Figure 2). The open circles represent the lateral position of the ball. On this trial, the ball was released at 1.07 m and ended at 44 cm to the right of the right eye. The open diamonds represent the observed hand positions. The hand started about 56 cm to the right of the eye, remained immobile until about $t = 0.46$, moved to the left, returned slightly to the right, and arrived at the interception point at $t = 0.00$.

Figure 7 also presents predicted hand movements. The predictions are shown by the filled dots, triangles, and squares for $\dot{\phi}/\dot{\theta}$, $\delta \times \dot{\theta}/\dot{\phi}$, and χ_{ball}, respectively. Note that, by and large, the filled squares accelerate toward the momentary position of the ball, and the filled triangles accelerate toward the interception point. The filled dots accelerate toward a smaller distance than the filled triangles because we used a larger than average ball on this trial, which led to a smaller passing distance in units of ball size. We made the predictions by numerically solving Equation 4 with an improved Euler method and a step size of 0.01 s (e.g., Boyce & DiPrima, 1977). The predictions started at the same moment, at the same position, and with the same speed as the actual movements. This means that the start of the movement was assumed rather than predicted. The moment of initiation was defined as the moment at which the actual hand velocity exceeded 10 cm/s. The model included a perceptual-motor delay of 0.10 s, as did the original required velocity model. We did not consider trials on which the movements started earlier than 0.10 s after the opening of the goggles (1.1% of all trials). The movements were simulated until 0.10 s after the goggles closed. For the particular trial and parameter values in Figure 7, χ_{ball} was the poorest predictor and $\dot{\theta}/\dot{\phi}$ the best, at least up to a time shortly after the goggles closed.

Before we examine the average errors, more detail is needed on the estimation of the six calibration parameters (c_1 and c_2 for each

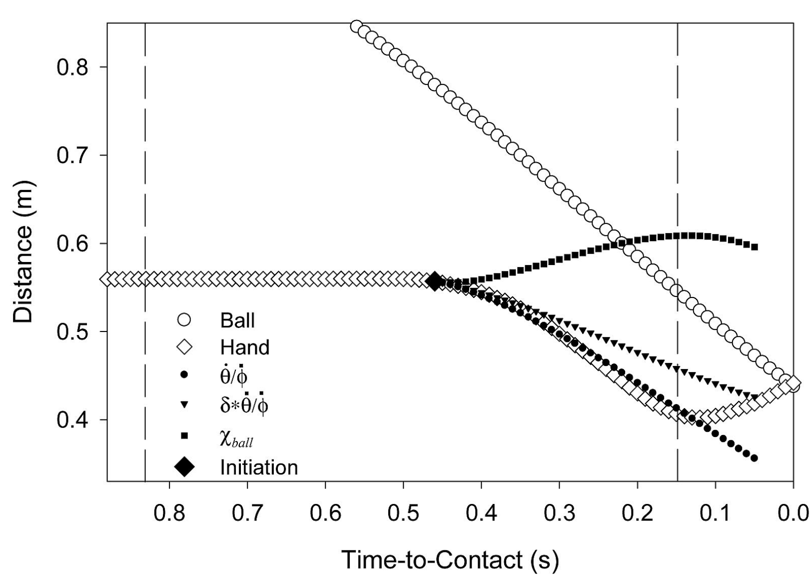

Figure 7. Lateral positions of the hand and ball in a single trial of Experiment 2, together with the hand positions predicted by the candidate optical variables in combination with Equation 4. To compare the depicted predictions, we used average rather than fitted values of the calibration parameters. The dashed verticals represent the opening and the closing of the goggles.

of the three optical variables). We used 61 values of c_1 and c_2, ranging from 0 to 60 in steps of 1.00 for c_1 and from 0.00 to 1.20 in steps of 0.02 for c_2. For each trial and each optical variable, we ran the simulations for all combinations of calibration parameters. We determined which combination of calibration parameters led to the best fit for each candidate variable per block of trials of each participant. The fit was defined as the distance between the predicted and observed hand positions, averaged first over the range of sampled positions within a trial for which predictions were made and then over all trials within a block. The values of c_1 and c_2 were lower than the highest considered values for all best fits. This indicates that using wider ranges of the parameters would not have improved the fits. The results presented below concern the best fits—the smallest average errors—and their associated parameter values.

Figure 8 shows the average errors for the best fits generated by each candidate variable, broken down by block of trials and observer. The errors are given on the vertical axes; the smaller errors are presented higher in the graphs to facilitate comparison with our earlier correlation plots. Thus, the higher curves represent more accurate predictions than do the lower curves. The squares generally lie lower than the other symbols, indicating that χ_{ball} explained the movement kinematics less well than did $\dot{\theta}/\dot{\phi}$ (dots) and $\delta \times \dot{\theta}/\dot{\phi}$ (triangles). The original required velocity model assumes the use of χ_{ball}. The large errors associated with χ_{ball} thus lead us to conclude that the original model, with the added constraint that the parameters α and β do not fluctuate independently, does not accurately predict the kinematics of the catches. The versions of the model with other input variables fare better.

The hand movements of one monocular catcher, Participant 1, seemed to be best predicted by $\delta \times \dot{\theta}/\dot{\phi}$. Participant 3 seemed to rely on $\dot{\theta}/\dot{\phi}$, and for Participants 2 and 4 it was difficult to distinguish whether they relied on $\dot{\theta}/\dot{\phi}$ or $\delta \times \dot{\theta}/\dot{\phi}$. The movements of the binocular catchers, Participants 5 to 8, were best explained by $\delta \times \dot{\theta}/\dot{\phi}$. The overall difference between the vision conditions is more clearly illustrated in Figure 9, which presents the difference between the average errors of $\dot{\theta}/\dot{\phi}$ and $\delta \times \dot{\theta}/\dot{\phi}$ per block of trials. For binocular catchers, the errors were larger for $\dot{\theta}/\dot{\phi}$ than for $\delta \times \dot{\theta}/\dot{\phi}$ in all blocks of trials. This was not the case for monocular catchers, who appeared to rely less on $\delta \times \dot{\theta}/\dot{\phi}$. We performed an ANOVA on the difference in errors; block (1 to 6) was a within-subjects factor, and vision (monocular, binocular) was a between-subjects factor. Both main effects were significant: $F(5, 30) = 2.6$, $p < .05$, for block, and $F(1, 6) = 8.8$, $p < .05$, for vision. Indeed, the difference in variable use between the vision conditions was significant. The interaction was not significant, $F(5, 30) = 2.0$, $p > .10$.

Note that, at first blush, Figure 8 does not reveal many changes in variable use. It is important, however, to keep in mind one of the limitations of our analyses. As with other commonly used analyses, such as ANOVAs and regression analyses, our analyses did not distinguish reliance on collinear or near-to-collinear variables. Therefore, where we—and many other authors—write "Observer X seemed to use Variable Y," one might add "or anything collinear with Variable Y." In fact, "Variable Y" stands for a range of variables (cf. Michaels & de Vries, 1998). This means that such analyses cannot reveal changes among collinear or near-to-collinear variables. Thus, the absence of large changes in Figure 8 implies that no changes occurred at the level of the considered

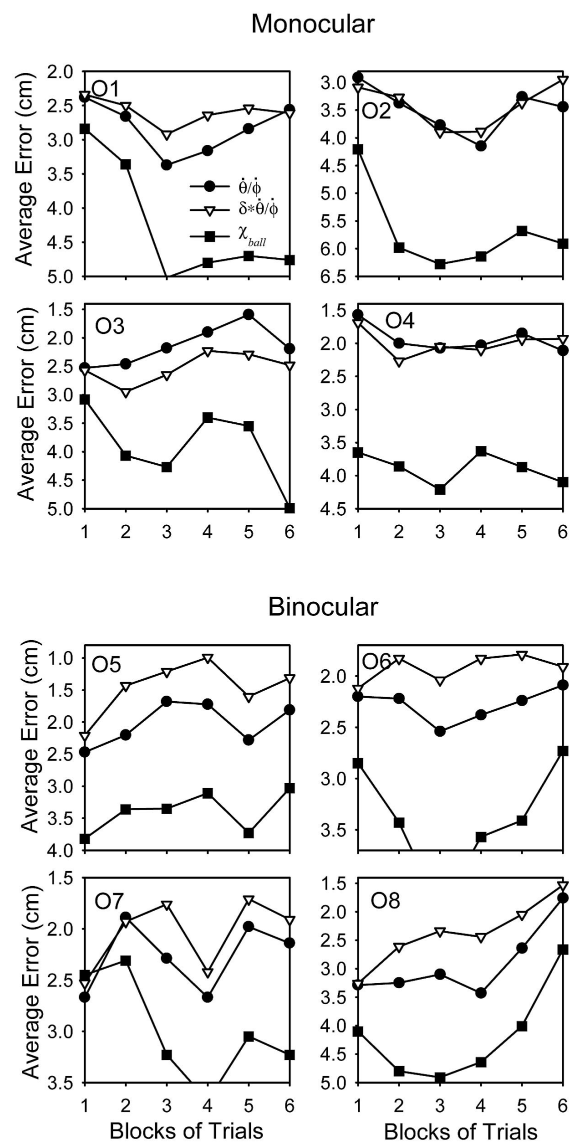

Figure 8. Differences between actual hand positions and the hand positions predicted by the use of the candidate optical variables in combination with Equation 4. The presented differences were averaged first over all sampled hand positions within a trial and then over all trials in a block. The calibration parameters were fitted per optical variable and per block of trials. O = observer.

candidates. So far, we have learned nothing about changes among variables that may be more similar to one of the candidates than to the others. This ambiguity is troubling, especially because one of the main goals of this study is to investigate whether actors change in variable use. We therefore explored whether there is evidence that more subtle changes in variable use occurred.

The optical variable used by a catcher at a particular phase of the experiment, together with the control law, should accurately explain the movement kinematics. If, as we assumed, a single optical variable is used, other optical variables should have no causal role in the movement generation. Nevertheless, other variables might also appear to explain the movement kinematics to the extent that

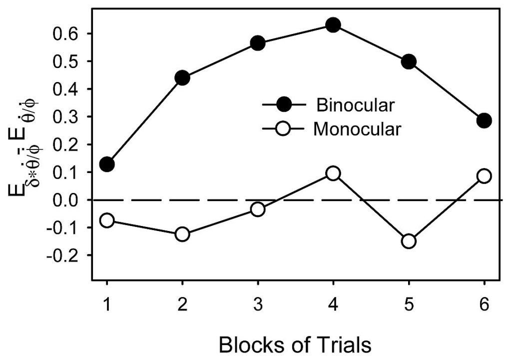

Figure 9. Difference in the error of the kinematics predicted by $\dot{\theta}/\dot{\phi}$ and $\delta \times \dot{\theta}/\dot{\phi}$, averaged per block of trials for monocular and binocular participants of Experiment 2.

they are similar to the used variable. In our experiments, the relations among the optical variables did not change over blocks, which implies that changes in variable use would normally result in changes in the relative explanatory value of the candidate variables. Searching for changes in the relative explanatory value of the candidate variables cannot reveal changes among variables that are completely collinear, but it may reveal changes among variables that are more similar to one of the candidate variables than to the others.

Consider again Participant 7 in Figure 8. His catches seemed to be best predicted by χ_{ball} in the pretest but by $\delta \times \dot{\theta}/\dot{\phi}$ in the latter blocks. Other catchers, for instance Participants 1 and 3, also seemed to show an increase in the explanatory value of $\delta \times \dot{\theta}/\dot{\phi}$ relative to the explanatory value of χ_{ball}. To test this, we computed the average errors associated to the use of $\delta \times \dot{\theta}/\dot{\phi}$ minus those associated to the use of χ_{ball} (see Figure 10). The differences were always positive, indicating, as expected, that $\delta \times \dot{\theta}/\dot{\phi}$ was a better predictor than χ_{ball}. We performed an ANOVA on the differences; block (1 to 6) was a within-subjects factor, and vision (monocular, binocular) was a between-subjects factor. Only the effect of block was significant, $F(5, 30) = 8.5$, $p < .001$, indicating that the difference increased over blocks. Although the used variable generally appeared to be more similar to $\delta \times \dot{\theta}/\dot{\phi}$ than to χ_{ball}, this increase seems to suggest that catchers changed from reliance on a variable that was also, to a certain extent, related to χ_{ball} to a variable that was less so related.

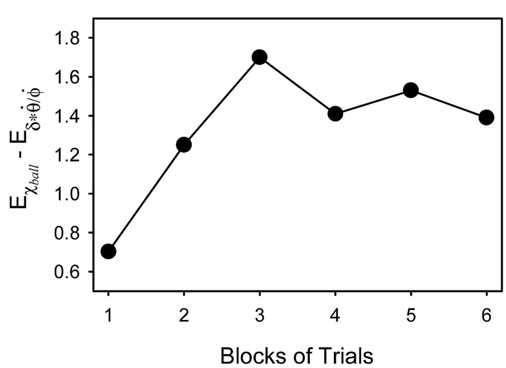

Figure 10. Difference in the error of the kinematics predicted by $\delta \times \dot{\theta}/\dot{\phi}$ and χ_{ball}, averaged per block of trials over all participants of Experiment 2.

Later in this article, we report several findings that add evidence in favor of such changes. Taken together, these findings illustrate that, although significant, the change in variable use was modest. We want to emphasize, however, that most of the effects reported in this section were large and robust. We have reliably demonstrated that χ_{ball} explained the kinematics of the catches less well than the other candidate variables, that $\delta \times \dot{\theta}/\dot{\phi}$ was the best predictor for binocular catchers, that monocular and binocular catchers differed in the variables they used, and that no large changes in variable use occurred.

Optical basis of the movement analyzed with a discrete action parameter. The previous analyses assume a continuous control law. This assumption seems reasonable because the control law was empirically supported by Peper et al. (1994) and Montagne et al. (1999, 2000) and because the differences between the predicted and observed kinematics were relatively small, on the order of 2.00–2.50 cm. Nevertheless, the model sometimes failed to predict qualitative aspects of the movements, such as the very end of the trajectory (see Figure 7). We postpone our efforts to obtain more precise models of lateral interception until our companion article (Michaels, Jacobs, & Bongers, 2006). In the present subsection we aim to ensure that our conclusions concerning variable use do not depend on the assumed continuous-control model; we test how well the three candidate variables predict a discrete action variable.

We examined several discrete action measures and present the results of one representative measure, hand velocity 0.5 s after the goggles opened. One can expect the hand velocity to depend both on where the hand starts and on optical variables related to the ball trajectory. We therefore used the difference between the starting position of the hand and values of the three candidate variables, at the moment the goggles opened, as our three predictor variables. Table 2 presents the squares of the correlations among the predictors. The less than perfect correlations indicate that, in the present collection of trials, the predictors were sufficiently different to be distinguished.

Figure 11 shows how well the different optical variables predicted the hand velocities; it presents the squared correlations

Table 2
Squared Correlations Among Predictor Variables in Experiments 2 and 3

Variable	1	2	3
Experiment 2			
1. $\dot{\theta}/\dot{\phi}$	—	.80	.02
2. $\delta \times \dot{\theta}/\dot{\phi}$		—	.02
3. χ_{ball}			—
Experiment 3			
1. $\dot{\theta}/\dot{\phi}$	—	.94	.23
2. $\delta \times \dot{\theta}/\dot{\phi}$		—	.24
3. χ_{ball}			—

Note. The predictor variables are the differences between the starting position of the hand and the positions specified by the candidate optical variables at the moment of goggle opening.

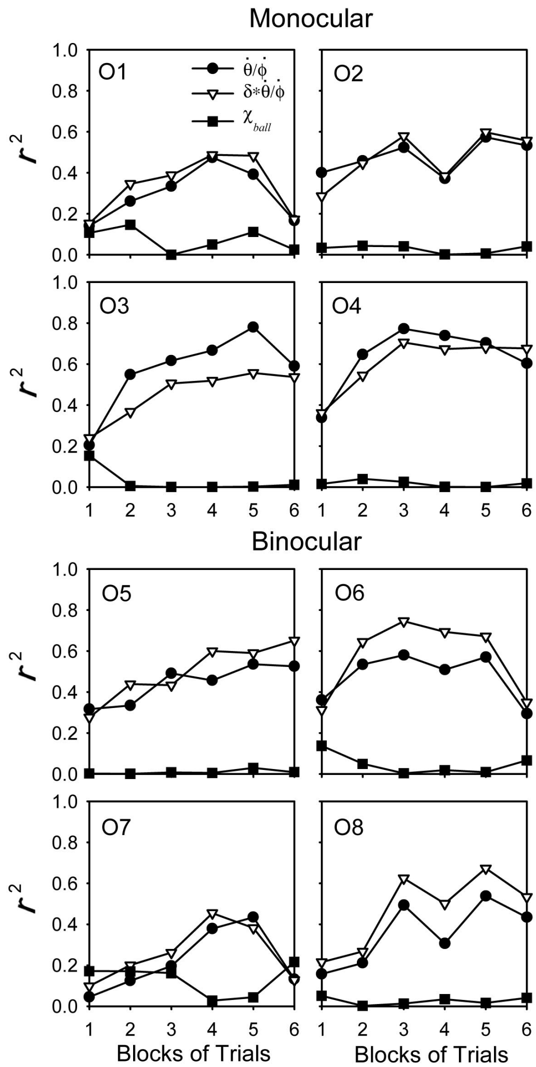

Figure 11. The squares of the correlations between the hand velocity 0.5 s after the opening of the goggles and the difference in the initial hand position and the positions specified by the candidate optical variables at the opening of the goggles, in Experiment 2. Each plot shows the results for one observer (O).

between the hand velocity and the predictor variables. Note that the figure is reasonably similar to Figure 8. A cursory inspection reveals that $\dot{\theta}/\dot{\phi}$ (dots) seemed to be the best predictor for Observers 3 and 4 and that $\delta \times \dot{\theta}/\dot{\phi}$ (triangles) was best for Observers 1, 5, 6, and 8. Overall, $\dot{\theta}/\dot{\phi}$ and $\delta \times \dot{\theta}/\dot{\phi}$ seemed to be the best predictors for monocular and binocular catchers, respectively. To further analyze this difference between the monocular and binocular conditions, we computed the dependent measure defined in Experiment 1: the difference between the z transformations of the correlations associated to $\dot{\theta}/\dot{\phi}$ and $\delta \times \dot{\theta}/\dot{\phi}$ (see Figure 12). For monocular participants, the dependent measure tended to be negative, indicating that the z transformations were larger for $\dot{\theta}/\dot{\phi}$ than for $\delta \times \dot{\theta}/\dot{\phi}$, and the converse was true for binocular participants. We performed an ANOVA on the dependent measure, with block (1 to 6) as a within-subjects factor and vision (monocular, binocular) as a between-subjects factor. Only the effect of vision was significant, $F(1, 6) = 7.6$, $p < .05$, consistent with the suggested difference in reliance on variables between monocular and binocular catchers.

The low correlation between the prediction with χ_{ball} and the other predictors ($r^2 < .03$) allowed us to assess the effect of χ_{ball} independently of the effect of the other variables. With a few exceptions, χ_{ball} (together with the starting position) did not seem to affect the hand velocity. Note that these exceptions tended to occur in the earlier blocks. In the first half of the experiment, the correlations for χ_{ball} were significant ($p < .05$) in 29.2% of the blocks, and in the second half of the experiment, these correlations were significant in 12.5% of the blocks. This is consistent with the suggestion that the operative optical variables came to be even less related to χ_{ball} after practice.

Calibration of the hand movement. Given the subtlety of the changes in variable use, it seems improbable that the large improvement in performance was due only to them. We next investigate whether there were also changes in calibration. We analyzed the best fitting calibration parameter values that we had found for the optical variable exploited by that participant on that block of trials (i.e., the variables corresponding to the highest symbol per block of trials in Figure 8).

Figure 13 presents the values of parameters c_1 and c_2 (upper and lower panels, respectively) for monocular and binocular observers (left and right panels, respectively). On average, c_1 was .83 in the pretest and .98 in the posttest, and c_2 was .65 in the pretest and .75 in the posttest. We performed separate ANOVAs on these parameters; block (pretest, posttest) was a within-subjects factor, and vision (monocular, binocular) was a between-subjects factor. For both parameters, the effect of block and the interaction were significant or tended toward significance: $F(1, 6) = 3.9$, $p < .10$, and $F(1, 6) = 6.8$, $p < .05$, for the effects of block on c_1 and c_2, respectively, two-tailed; and $F(1, 6) = 8.8$, $p < .05$, and $F(1, 6) = 4.8$, $p < .10$, respectively, for the interactions. The effects of vision were not significant, $F(1, 6) = 0.9$, $p > .10$, and $F(1, 6) = 1.1$, $p > .10$.

Recall that c_1 related a particular difference in actual and required velocity to a particular acceleration. Accordingly, the apparent increase in c_1 suggests that the same velocity difference led to a higher acceleration in the posttest than in the pretest. The

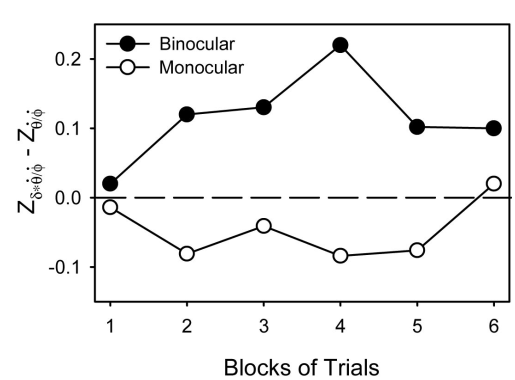

Figure 12. Difference in the z transformations of the correlations between the velocity 500 ms after the catch and the predictor variables based on $\dot{\theta}/\dot{\phi}$ and $\delta \times \dot{\theta}/\dot{\phi}$, averaged per block of trials for monocular and binocular participants of Experiment 2.

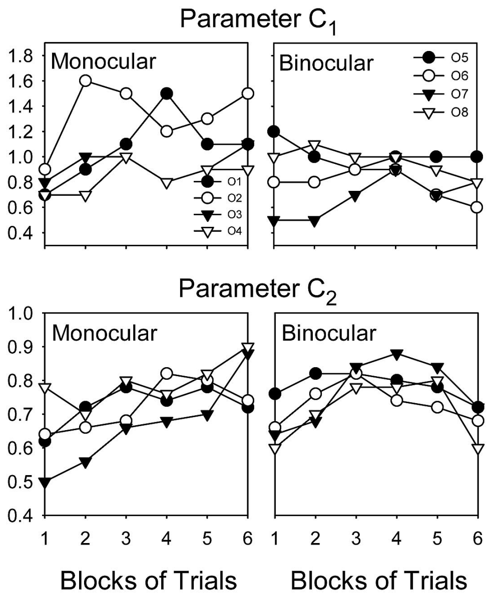

Figure 13. Calibration parameters determined for Experiment 2. The top panels show c_1, which relates acceleration to the optical variable. The bottom panels show c_2, which relates optical to hand variables. O = observer.

increase in c_2 means that catchers used progressively lower values of the optical variables compared with the values of the (presumably) kinesthetic information about hand position. Finally, the interactions indicate that the changes were mainly due to the monocular condition.

The results of Experiment 2 can be summarized by three points. First, the precision of the catches improved with practice. Second, the lateral hand movements of catchers appeared to be based on $\dot{\theta}/\dot{\phi}$ for monocular catchers and on $\delta \times \dot{\theta}/\dot{\phi}$ for binocular catchers. Third, the improvement of the catches was at least partly attributable to changes in calibration, as measured by parameters in the applied control law, and to small changes in variable use.

Experiment 3

In Experiment 2 and the published experiments on which it was based, catchers moved their hands along a bar, in a single dimension. Consequently, attempts to model catching in this task concerned lateral hand movements with one degree of freedom. The control law that we used in Experiment 2 shows how that degree of freedom can be constrained by optical variables. In more natural situations, however, and also in the present experiment, catchers are free to move in three dimensions. This means that they can intercept balls at a range of points in the trajectory. How are the additional degrees of freedom in such more natural conditions constrained?

First, catchers in more natural situations might move along a straight line, similar to catchers who are forced to move along a straight line. Such a strategy would freeze the added degree of freedom and allow the optical variables implicated in Experiments 1 and 2 to operate as in the previous experiments. Second, balls that pass at different lateral distances might be intercepted at different points in the trajectories. This strategy would result in catches that are distributed along a line that is not parallel to the frontoparallel plane or along a curve. Finally, the points in the trajectory at which the balls are intercepted could be affected by characteristics of the approach other than the lateral passing distance, which implies that the catches may not be distributed along a single line or curve. This final alternative requires informational constraints additional to those identified already.

The present experiment, therefore, investigates (a) how the additional degrees of freedom of three-dimensional catches are constrained and (b) whether the main findings of Experiment 2 generalize to three-dimensional catches.

Method

Experiment 3 was the same as the practice phase of Experiment 2, with the following exceptions. Eight new participants (mean age = 28 years; range = 19–51) were asked to catch the balls on all blocks of trials; there were no pre- or posttests. All participants reported normal or corrected-to-normal vision, and their stereoacuity was at least 60 s arc^{-1}. The hand movements were not restricted to a single dimension. The hand started at the passing height of the balls, 1.62 m behind the lowest point in the ball trajectories, just in front of the eye plane, either at 10 cm to the left of the shortest passing distance or at 10 cm to the right of the longest passing distance. A hand rest was used for the farther starting position but not for the closer one, because the hand could comfortably and accurately be held at the closer starting position, and a hand rest at that position would have hindered the catches. The goggles (only the right glass for monocular catchers) opened between 0.6 and 0.8 s after the ball was released and closed only after the ball was caught (or missed). The coordinates of a marker on the back of the hand were registered by the Optotrak system at 200 Hz. Three blocks of 60 trials were run in a single 2-hr session.

Results and Discussion

In this section, we address the improvement with practice, the optical basis of the hand movements and changes therein, and the distribution and control of movements in the anterior–posterior direction.

Improvement with practice. On average, participants caught 48% of the balls in Block 1, 63% in Block 2, and 64% in Block 3. Monocular catchers caught 52% of the balls, and binocular catchers 65%. Catchers missed (i.e., did not catch or touch) 15% of the balls in Block 1, 5% in Block 2, and 3% in Blocks 3. We performed an ANOVA on the number of catches; block (1 to 3) was a within-subjects factor, and vision (monocular, binocular) was a between-subjects factor. Only the effect of block was significant, $F(2, 12) = 29.1$, $p < .01$; indeed, catchers caught more balls after practice.

Optical basis of the hand movement. In Experiment 2, we used a discrete action parameter and a continuous control law to analyze which optical variables catchers relied on. The two analyses led to similar conclusions. Here we used only a discrete action parameter, mainly because the control law assumed in Experiment 2 does not apply to three-dimensional catches. As in Experiment 2, the dependent variable was the lateral velocity of the hand 0.5 s after the goggles opened, and the predictor variables were the differences between the starting positions of the hand and the ball positions specified by the candidate variables at the opening of the goggles. Table 2 gives the squares of the correlations among the predictors. The correlations differed from those in Experiment 2 because we used only two starting positions of the hand. Unfortunately, the correlation between the predictors based on $\dot{\theta}/\dot{\phi}$ and on $\delta \times \dot{\theta}/\dot{\phi}$ was high ($r^2 = .94$). Because of this collinearity, we did not attempt to distinguish these two predictors and considered only the predictions with $\delta \times \dot{\theta}/\dot{\phi}$ and χ_{ball}.

The hand velocity correlated significantly more highly with the predictions of $\delta \times \dot{\theta}/\dot{\phi}$ than with those of χ_{ball} in each block of trials of each catcher ($p < .05$). This is consistent with the finding that catchers used $\delta \times \dot{\theta}/\dot{\phi}$ or any variable collinear with $\delta \times \dot{\theta}/\dot{\phi}$ (including $\dot{\theta}/\dot{\phi}$). As in Experiment 2, hand velocity did not appear to correlate highly with χ_{ball}. Several findings of Experiment 2 indicate that χ_{ball} came to affect the catches even less after practice. In the present experiment, the predictions with $\delta \times \dot{\theta}/\dot{\phi}$ and χ_{ball} were correlated. To single out the effect of χ_{ball}, we computed the partial correlations between the hand velocity and χ_{ball}, controlling for $\delta \times \dot{\theta}/\dot{\phi}$. The average squared correlations were .12, .08, and .04 for Blocks 1 to 3, respectively. A one-way repeated-measures ANOVA on the z transformations of these correlations revealed that the decrease over blocks was marginally significant, $F(2, 14) = 2.6$, $p < .06$, single-tailed. Again, χ_{ball} did not affect the catches very much before practice, and it did so even less after practice.

Distribution of catching/touching locations. The following analyses concern the position of the hand marker at the moment of interception for trials in which participants caught or touched the ball. Because the heights of the initial position and of the interception were largely implied by the instructions and by the ball trajectory, we limited the analyses to the x (lateral) and y directions (anterior–posterior). Catchers were reasonably able to hold their hands at the instructed initial positions. The average standard deviations of the x and y coordinates of the hand at the moment of ball release were 1.9 and 1.4 cm for the farther initial position, which used a hand rest, and 2.6 and 3.3 cm for the nearer initial position, which did not use a hand rest.

To give an impression of where the balls were intercepted, we present three blocks of trials as examples (see Figure 14). The large circles indicate the average initial position for the trials that used the nearer starting point, and the small open circles indicate the positions of the hand at the moment of interception for those trials. The large and small filled circles represent these positions for trials that used the farther initial position. The figure illustrates four findings, which we statistically confirm in the following paragraph. First, the y coordinates at the interception were generally positive, indicating that the balls were intercepted before they reached the eye plane. Second, there appeared to be some linear relation between the x coordinates (or passing distances) and the y coordinates. In Block 3 of Catcher 2 (left panel), balls with a shorter passing distance appeared to be intercepted closer to the eye plane, and the converse seemed to be true for Block 2 of Catcher 8 (right panel). Third, individuals seemed to differ in where they intercepted the balls. Finally, the catching positions were not distributed perfectly along single lines, which suggests that passing distance was not the only predictor of the interception point.

To test the reliability of these findings, we performed linear regression analyses for all catchers with the x coordinate of the hand at the interception as the independent variable and the y coordinate as the dependent variable. The results of these analyses are presented in Table 3, along with the means and standard deviations of the y coordinates. The means of the y coordinate differed significantly from zero, $t(7) = 6.7$, $p < .001$; the balls were indeed intercepted before they reached the eye plane. Six of the eight regression models were significant, indicating linear relations between the x and y coordinates and thus dependence of the interception position on passing distance. The different slopes and signs of the slopes mean that these relations were different for different catchers. Finally, the correlations of the regression models were low, suggesting that the x coordinate was not a very good predictor of the y coordinate.

To determine whether other variables were related to the distributions of the catches in the anterior–posterior direction, we performed multiple regressions that compared the y coordinate of the hand at the moment of interception with the x coordinate of the hand at interception, the hand's starting position, and a variety of optical variables, including the above-described candidate variables and tau-type variables. Of the 24 (Block $\times$ Participant) regressions, 4 had no significant predictors, 15 showed one or both of the hand-position predictors (i.e., the x coordinate of the hand at

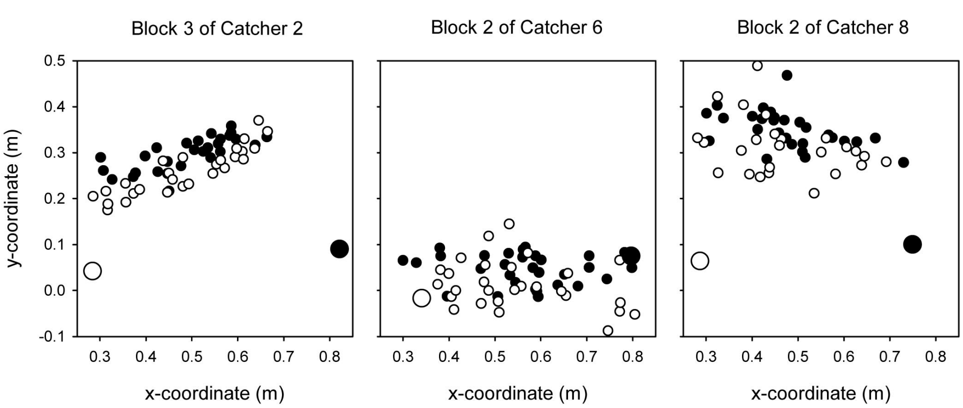

Figure 14. Initial hand positions and interception points for three exemplar blocks of trials. Each panel gives the results of one block of trials. The large open circles represent the average observed starting position for trials in which the nearer initial position was used, and the small circles represent the interception points of those trials. The solid circles are associated likewise to the farther starting position.

Table 3
Means and Standard Deviations of y Coordinate at the Moment of the Catch and the Results of Regression Analyses With x Coordinate as Independent Variable and y Coordinate as Dependent Variable for Balls That Were Caught or Touched in Experiment 3

Catcher	M	SD	r	F	p	Constant	Slope
1	.32	.069	.13	2.4	.122	.36	−.11
2	.27	.053	.63	104.5	.001	.12	.29
3	.28	.053	.24	9.2	.003	.23	.12
4	.15	.049	.37	24.5	.001	.07	.17
5	.28	.048	.20	6.8	.010	.31	−.09
6	.03	.057	.06	0.7	.407	.05	−.03
7	.25	.061	.28	14.8	.001	.17	.15
8	.33	.061	.26	12.3	.001	.41	−.16

interception and/or the starting position), and 5 had tau-type variables significant in addition to hand-position predictors. Those 5, however, did not show any patterns within participants that suggested that participants learned to use or not use variables for the special control of the anterior–posterior movement. Instead, the frequent association with the hand-position variables seems to imply either that variation in the *y* coordinate is, to a certain extent, biomechanical in origin (e.g., arising from comfortable *x*–*y* combinations) or that the *y* coordinate is informed by the same optical variables that inform lateral position.

To summarize the results of Experiment 3, we note that the improvement after practice, the superior explanatory value of $\dot{\theta}/\dot{\phi}$ and $\delta \times \dot{\theta}/\dot{\phi}$ with respect to χ_{ball}, and the subtle change in variable use that we found in Experiment 2, in which the hand of catchers was constrained to move in a single dimension, appeared to generalize to three-dimensional catches. Catchers did not restrict their points of interception to a single line, but we could not isolate optical variables that predicted the variation in the anterior–posterior position of the catches; instead, the anterior–posterior position covaried most systematically with the initial or final lateral hand position.

General Discussion

In the present study, we set out to examine the changes underlying the typical improvement in perception and action with practice. The main purpose was to determine whether attunement to the more useful variables, previously demonstrated with judgments made in response to two-dimensional simulations, also occurs in judgments of real events and in visually guided action. We chose as tasks judging the lateral passing distance of balls and lateral interception of balls. We aimed to reveal (a) the optical variables used, (b) the extent to which perceivers and actors show individual differences and changes in variable use, and (c) the extent to which perceivers and actors show differences and changes in calibration.

In all experiments, adult participants observed balls that passed at small sideward distances. In Experiment 1, they made verbal estimates of passing distance. The judgments improved substantially after practice with feedback, as indicated, for instance, by a decrease in absolute error. Overall, the judgments were best explained by the optical variable $\delta \times \dot{\theta}/\dot{\phi}$ in the binocular condition and, less clearly, by the variable $\dot{\theta}/\dot{\phi}$ in the monocular condition. Changes in the correlations over blocks implied that observers occasionally changed in their attunement to optical variables; in J. J. Gibson's (1966, 1979) terminology, they occasionally educated their attention to the more useful ones. Calibration also improved with practice. Thus, the increased accuracy of judgments of real events should at least partly be attributed to attunement and calibration.

Participants in Experiments 2 and 3 were asked to actually catch the balls, with their hands either restricted to move in a single dimension along a bar or free to move in three dimensions. In both experiments, the number of catches increased with practice. As were the judgments, the movement kinematics were best explained by $\delta \times \dot{\theta}/\dot{\phi}$ for binocular catchers and, less clearly, by $\dot{\theta}/\dot{\phi}$ for monocular catchers. Several findings indicated that admittedly subtle changes in attunement occurred. Although the operative optical variables were more similar to $\dot{\theta}/\dot{\phi}$ and $\delta \times \dot{\theta}/\dot{\phi}$ than to χ_{ball} at all phases of the experiment, they were also, to a certain extent, related to χ_{ball} before practice, but less so after practice. Remembering that $\delta \times \dot{\theta}/\dot{\phi}$ and χ_{ball} are related to future passing distance and momentary lateral ball position, respectively, one could say that catchers learned to be slightly less affected by the momentary lateral position of the ball and thus came to move more directly toward the future interception point.

In Experiment 2 we also tested for and observed changes in calibration. We interpreted parameters in an assumed control law as the calibration between optical and (presumably) kinesthetic information about lateral distance and between the required acceleration and a higher order informational variable. The same values of the higher order variable seemed to yield higher accelerations after practice than before. Similarly, after practice, lower values of the optical variables came to be associated to the same values of the kinesthetic patterns. These changes in calibration are consistent with previous calibration studies that used other actions as dependent measures (e.g., Bingham & Romack, 1999; Rieser, Pick, Ashmead, & Garing, 1995).

Note that we do not claim that the improvement in performance was due only to changes in variable use and calibration. We hypothesize, for instance, that factors such as finger coordination also contribute to improvements such as the increase in the number of catches. The contribution of factors not considered in the present study is especially likely given that the observed improvements in performance were considerably large and the observed changes in, for instance, variable use were not.

Because one of our main goals was to generalize the change in variable use previously reported in simulation-judgment studies, we are particularly interested in the finding that we observed less change in variable use using an arguably more natural task. It is illustrative to compare the change in Figures 4, 8, and 11 with, for instance, the change in Experiment 3 of Jacobs, Runeson, and Michaels (2001), in which the relative mass of simulated colliding balls was judged. For several participants in that experiment, the squared correlation for one candidate variable increased from, for instance, .24 to .65, whereas the squared correlation for another candidate variable decreased from .69 to .22. Before we conclude this article, we consider two possible explanations for the finding that less change in variable use is found in apparently more natural tasks, in which participants are de facto more experienced.

A first hypothesis is that experience leads to structural change in perceptual and perceptual-motor systems. That is, the mechanisms underlying attunement might be more sensitive to feedback in novices than in experts. In the extreme, experts might not change their attunement at all. Note that this would not be inconsistent with the change observed in the present experiments because, although the catching task intuitively appears more natural than does judging kinetic properties from two-dimensional simulations, it is less natural than many other tasks, such as catching balls that fly through the air.

A second hypothesis is that experts are as sensitive as novices to feedback but show less change because they already exploit useful variables, meaning that the feedback informs them not to change. Adopting this second hypothesis has the advantage that it would allow one to explain performance and flexibility in performance of novices and experts using the same principles (see also Jacobs, 2001; Jacobs & Michaels, 2005). The following analogy illustrates this.

Consider changes in temperature controlled by a thermostat. Such change is easily observable only for temperatures that begin well outside the intended temperature range, but the mechanisms underlying the thermostat are the same if the temperature lies inside or close to that range. Analogously, the same mechanisms might underlie learning in experts and novices, despite the smaller amount of observable change in experts. Under this interpretation, experts show less change merely because the variables they use are more similar to the most useful ones.

The thermostat analogy also illustrates why we think that differences among participants and changes in variable use are important for studies investigating which optical variables constrain perception and action. The principles behind a thermostat are independent of a particular temperature, and, analogously, the principles governing perception and action might be independent of the operative optical variable. Studying the variables that constrain perception and action provides information about the state of perceptual and perceptual-motor systems rather than information about the nature of the systems themselves. The state of a system can also be relevant, of course, but more so if one assumes that it does not change too easily. The present results indicate that this assumption is to a larger extent tenable in natural as compared with laboratory situations.

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